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PREPRINT

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

The use of microwave radiometry for the remote sensing of soil moisture has been studied in a series of aircraft flights over agricultural test areas in the southwestern U.S. The radiometers covered the wavelength range 0.8 cm to 21 cm. Ground truth in the form of gravimetric soil moisture measurements were obtained at each test site. The results indicate that it is possible to monitor soil moisture variations with airborne radiometers. The emission, in general, is not a linear function of soil moisture and is affected by soil type and surface conditions such as roughness and vegetative cover.

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REMOTE SENSING OF SOIL MOISTURE WITH MICROWAVE RADIOMETERS

INTRODUCTION

There is considerable interest in remotely sensing the moisture content of soils because of the difficulty in making direct measurements over large areas or in inaccessible areas. For example, meteorologists are interested in monitoring the moisture content of soil over extended areas to learn more about the mass and energy exchange at the air-soil interface. Hydrologists are interested in this information for predicting run-off.

Since the dielectric constant of water at microwave frequencies is quite large, as much as 80, while that of dry soil is typically less than 5, the water content of a soil can greatly affect its dielectric properties. The resulting emissivity for a soil has been observed for a bare, smooth field (Poe, et al., 1971) to vary from 0.5 for very wet soil to greater than 0.9 for a dry soil. The effect was observed to increase with increasing wavelength in the wavelength range 0.8 to 21 cm, with the horizontal polarization being more effective than the vertical at each wavelength.

To test the use of this approach for the remote sensing of soil moisture, microwave radiometers were flown on board the NASA Convair 990 Airborne Observatory over agricultural test sites in southwestern U.S. during February and March of 1971. Extensive ground truth data were obtained simultaneously with the flights. This report is a discussion of the results from these flights. The frequency dependence of the emission from soils will be discussed along with the effects of surface roughness, vegetative cover and soil type.

Experimental

The microwave radiometers used in this study are listed in Table 1. Surface temperatures were measured using a nadir-viewing infrared radiometer operating in the 10-12 micrometer atmospheric window. A 70 mm nadir-viewing camera with Kodak 2443 Aerochrome infrared film was used for determining the flight path of the aircraft.

The agricultural test sites were located in the vicinity of Phoenix, Arizona, and Weslaco, Texas, and in the Imperial Valley of Southern California. Ground truth data in the form of gravimetric soil moisture measurements were obtained for selected target fields at each site. The soil moisture values are expressed as weight percent, determined by the formula

$$\% \text{ soil moisture} = \frac{\text{wet weight - dry weight}}{\text{dry weight}} \times 100,$$

where the dry weight was obtained after heating for 24 hours at a temperature of 105°C.

The majority of the selected fields were without vegetative cover and at least 400 meters on a side. In the Imperial Valley and Phoenix area, four 15 cm soil samples were taken in each field to yield the average soil moisture for the top 15 cm in the soil (Biospherics, Inc., 1971).

More detailed surface truth data were available for the flights over the Weslaco, Texas area through a cooperative effort with the Remote Sensing Center of Texas A&M University (Jean, 1971), and the USDA Agricultural Research Station at Weslaco. In this study, a surface sample, 1-3 cm deep, and a subsurface sample at a depth of 15 cm were taken; data were obtained for 48 fields 1-3 days prior to the aircraft overflights. In addition, soil surface temperatures were determined with a portable ground-based Barnes Engineering Co. PRT-5 infrared radiometer.

Table 2 is a listing of the times at which the plane was over the target areas along with a brief description of meteorological conditions at the time of flight.

Table 1

Microwave Radiometer Characteristics

Freq. GHz	Wave Length cm	Pointing Relative to Nadir	3 db Beam Width	Integration Time Sec	RMS Temp. Sens.
1.42	21.1	0°	15°	0.1	5°K
4.99	6.01	0°	5°	0.1	15°K
19.35 H	1.55	Scanner	2.8°	0.025	1.5°K
37 V	0.81	45°	5°	0.1	3.5°K
37 H	0.81	45°	5°	0.1	3.5°K

Table 2

Date	Flight No.	Site	Number of Legs	Altitude Above Ground	Local Standard Time	Meteorological Conditions
Feb. 25, 1971	1	Imperial Valley 50 Fields	2	0.9 km	14:15-14:35 PST	Light haze, but otherwise clear. 100% of possible sunshine. Air Temp. = 24° C
Feb. 25, 1971	1	Phoenix, Ariz. 200 Fields	2	0.9 km	16:57-17:11 MST	Clear, 100% of possible sunshine, visibility = 30 miles. Air Temp. = 22° C
Feb. 25, 1971	1	Imperial Valley 50 Fields	2	0.9 km	17:03-17:26 PST	More haze than earlier pass otherwise the same. Air Temp. = 24° C
March 1, 1971	3	Phoenix, Ariz. 100 Fields	2	0.9 km	13:34-13:45 MST	70-80% cloud cover above aircraft at 0.9 km. Ground visible only 25% from 3 km. 68% of possible sunshine. Air Temp. = 13° C
March 1, 1971	3	Weslaco, Texas 48 Fields	1	0.9 km	16:50-17:00 CST	Scattered puffy cumulus between 0.9 and 3.0 km. Thin cirrus above and light haze below these levels. Air Temp. = 27° C
March 2, 1971	4	Weslaco, Texas 48 Fields	1	0.9 km	13:33-13:43 CST	Scattered cumulus and considerable low level haze. Air Temp. = 31° C

The specific times over the target fields and the accuracy with which the aircraft followed the desired track were determined from the photography. The required accuracy for tracking was such that the sub-nadir point be further than 100 meters from any field boundary; at this distance, over 90% of the 3 db beam width for the 1.42 GHz radiometer was within the field of interest.

Soil Types

Textural analysis of typical soils from each area has been performed. The results are illustrated in the soil-texture triangle shown in Figure 1. The different samples are identified in Table 3. These texture designations are based on the U.S. Department of Agriculture's soil-particle-fraction classification.

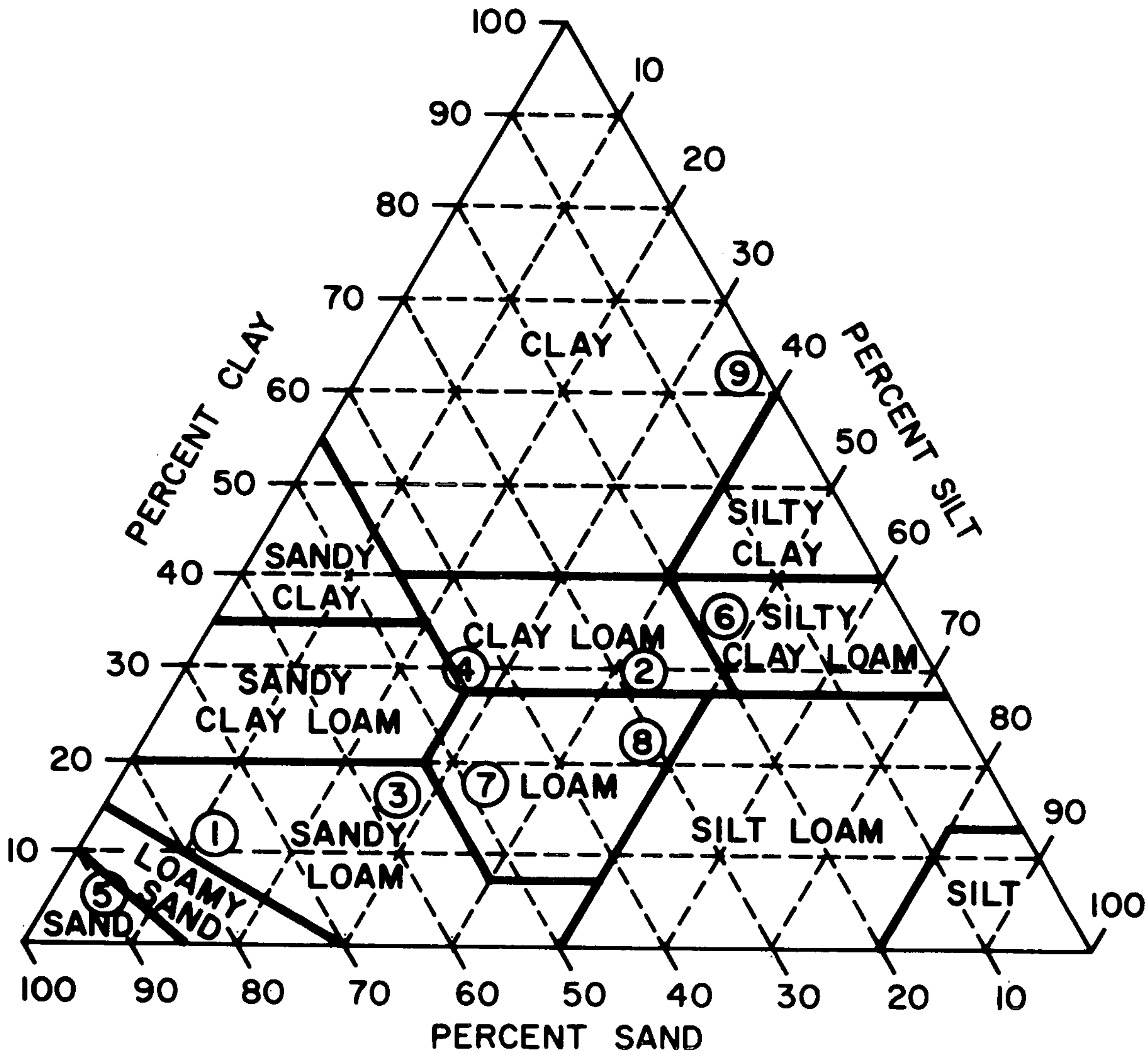

Figure 1. Soil-Texture Triangle (U.S. Department of Agriculture)

Table 3

Textural Analysis of Soils from Target Fields

No.	Site	Sand	Silt	Clay	Texture
1	Imperial Valley	76	12	12	Sandy Loam
2	Imperial Valley	27	43	30	Clay Loam
3	Phoenix, Ariz.	56	27	17	Sandy Loam
4	Phoenix, Ariz.	45	25	30	Clay Loam
5	Phoenix, Ariz.	88	8	4	Sand
6	Phoenix, Ariz.	19	46	35	Silty Clay Loam
7	Phoenix, Ariz.	48	34	18	Loam
8	Phoenix, Ariz.	32	46	22	Loam (Adelanto Loam)*
9	Weslaco, Texas	2	37	61	Clay (Harlingen Clay)**

*From Dr. Ray Jackson, U.S. Water Conservation Laboratory, Phoenix, Arizona.
**From Heilman, M. D., et al. – U.S.D.A. SWC Research Report 382.

The textures are expressed as the percentage of the 3 components: sand, silt, and clay which are defined by the following size ranges:

Clay: less than 2 microns (0.002 mm)

Silt: between 0.002 mm and 0.05 mm

Sand: between 0.05 mm and 2 mm

Sample No. 8, Adelanto Loam, is the soil type used for the ground based measurements of Poe, et al. (1971). The samples from the Imperial Valley represent the extremes of the soil textures in the valley and covers approximately the same range as those from Phoenix. The soil along the flight path at Weslaco, Texas is quite uniform and is represented by a single sample, No. 9, Harlingen Clay.

Information on the soil textures is important because of the differences in the behavior of water in soils with different textures. Thus, in general, the larger the clay fraction the greater is the water holding capacity of the soil. This is demonstrated by the variation of the wilting point for soils with different textures. The wilting point may be defined as the soil moisture condition at which the release of water to the plant is too small to counterbalance transpiration losses. At this point, there are about 5 or 6 molecular layers of H_2O around the soil particles (Kohnke, 1968). This water has a structure similar to that of ice and thus would not have the same dielectric properties as the free water located in the pore spaces between particles. The wilting points range from a high 22% for the Harlingen clay to about 5% for a sandy soil. The loamy soils would be somewhere in between, e.g., Adelanto loam has a wilting point of 10.4%.

RESULTS

The brightness temperature results will be presented in two groups. The first will be the multi-frequency results for those fields which were directly under the flight path of the aircraft. The second group is the listing of fields including those off-nadir which were in the field of view of the 1.55 cm scanning radiometer. This group includes essentially all of the target fields.

MULTI-FREQUENCY OBSERVATIONS

In Figure 2, line plots of the results from the 4 microwave radiometers and the infrared radiometer are presented. All of the data were computer-processed to obtain a one-second integration time. These data are from the early pass over the south leg at the Imperial Valley where the aircraft is flying in a westerly direction from a desert area over an irrigation canal (40 meters wide) into the cultivated area. The stretch over the desert gives an indication of the relative noise of the instruments. At a ground speed of 250 knots, it takes 3 seconds to overfly the typical 400 meter (1/4 mile) field; this distance is indicated in the figure.

The brightness temperatures for the target fields were determined from a listing of the one second averages of the brightness temperatures. The results are presented in Tables 4 through 8 for two passes over the Imperial Valley and Phoenix and a single pass over the Weslaco test site. For the Weslaco data given in Table 8, the soil moistures presented are those from the surface. The sub-surface values can be found in Table 11 where the off-nadir 1.55 cm results are presented. In general, the sub-surface samples are more moist and show less variation among the fields sampled.

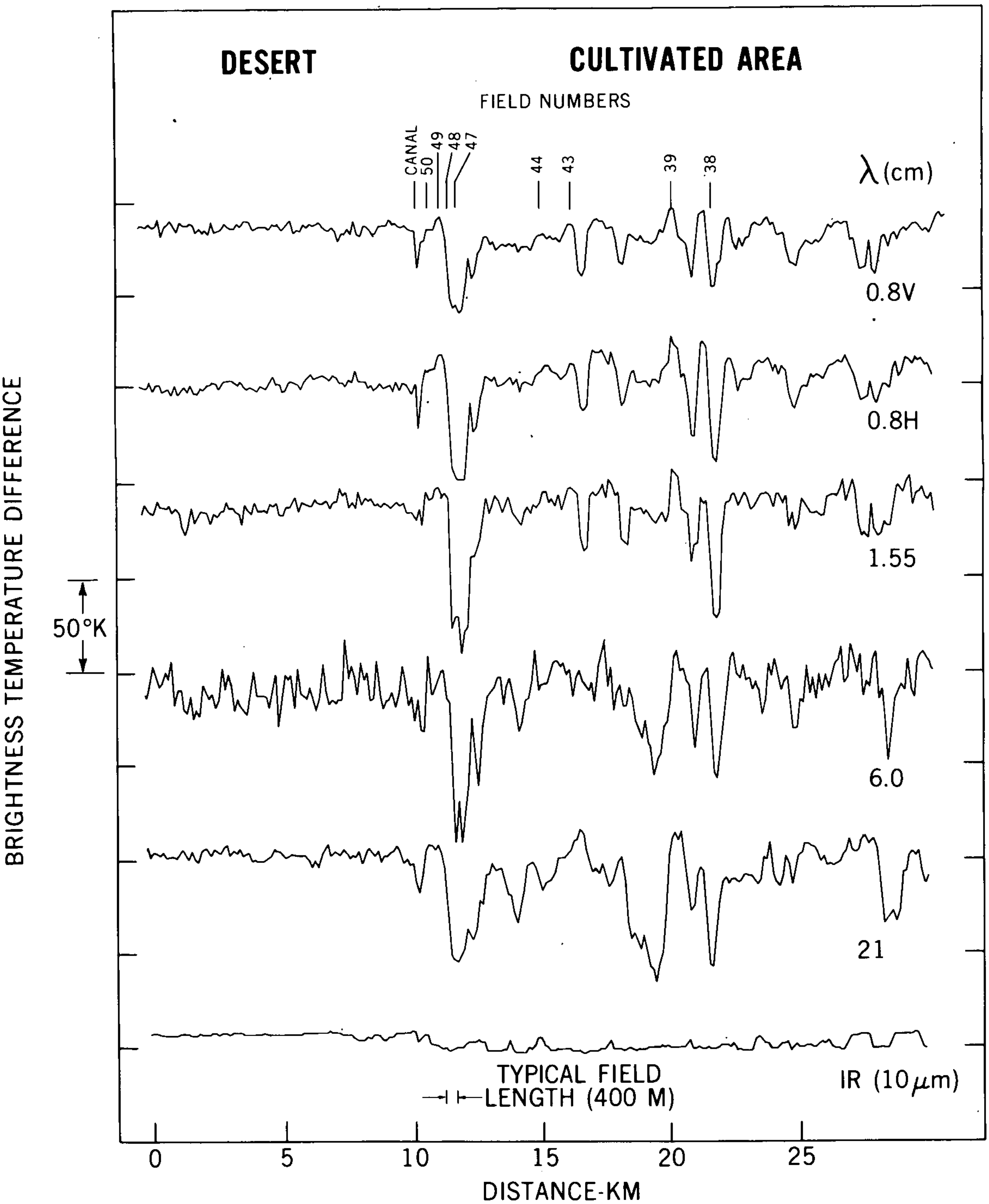

Figure 2. Microwave Brightness Temperature Records for the South Leg at the Imperial Valley. Field numbers are those listed in Table 4. The H and V indicate the horizontal and vertical polarizations of the 0.8 cm radiometer which viewed the surface at an angle 45°. The other radiometers were nadir viewing.

Table 4

BRIGHTNESS TEMP RESULTS FROM ...IMPERIAL VALLEY FLIGHT NO. 1

DATE FEB. 25 ,1971 TIME 14:15 TO 14:35 LST

FIELD NO	SOIL MOIST	IR TEMP	WAVELENGTH IN CM 21.1	6.01	1.55	0.8H	0.8V	FIELD CONDITIONS
E12	6.2	299	286	300	280	298	318	BARE,CULTIVATED
E11	7.4	300	281	307	282	299	318	BARE,CULTIVATED
E13	11.0	299	282	284	283	294	315	BARE,CULTIVATED
E14	11.7	298	280	302	283	300	318	BARE,CULTIVATED
E44	12.8	300	267	301	272	289	308	ALFALFA,12 INCH
E35	13.6	306	263	300	267	278	301	BARLEY,10 INCH
E39	13.9	300	290	309	282	300	320	BARE,CULTIVATED
E50	17.2	302	286	295	275	288	312	BARLEY,SPARSE
E49	19.0	300	283	298	273	294	315	BARE,CULTIVATED
E10	19.4	299	282	288	277	296	318	BARE,IN COTTON
E43	20.6	299	285	295	273	290	314	BARLEY,SPARSE
E9	21.4	303	278	291	274	293	313	BARE,IN COTTON
E2	22.2	304	257	290	263	282	303	ALFALFA 12 INCH
E38	23.0	299	215	251	209	238	277	BARE,CULTIVATED
E48	24.5	299	222	218	209	232	272	BARE,CULTIVATED
E6	30.8	312	268	292	252	268	292	BARE,IN COTTON
E47	31.2	301	224	225	200	229	270	BARE,CULTIVATED
E3	35.4	304	243	251	236	266	296	BARE,STANDING WATER
E5	36.1	298	238	262	241	265	292	BARE,IN COTTON
E4	37.0	297	230	257	238	262	290	BARE,IN COTTON

LINEAR REGRESSION RESULTS

INTERCEPT	301.1	321.2	299.9	311.7	327.5	DEGREES KELVIN
SLOPE	-1.84	-1.95	-2.00	-1.62	-1.18	DEGREES K/% SOIL MOISTURE
STD ERR OF ESTIMATE	18.6	20.4	19.7	17.6	12.1	DEGREES KELVIN
CORRELATION	0.692	0.681	0.702	0.667	0.686	COEFFICIENT

Table 5

BRIGHTNESS TEMP RESULTS FROM ...IMPERIAL VALLEY FLIGHT NO. 1

DATE FEB. 25 ,1971 TIME 17: 3 TO 17:26 LST

FIELD NO	SOIL MOIST	IR TEMP	WAVELENGTH IN CM 21.1	6.01	1.55	0.8H	0.8V	FIELD CONDITIONS
L01	3.0	294	259	278	268	274	306	BARE,NOT CULT
L37	5.7	295	287	302	272	283	309	BARE,CULT,FALLOW
L36	6.2	296	269	293	273	283	310	BARE,CULT,FALLOW
L44	12.8	295	261	289	272	283	305	ALFALFA,12 INCH
L35	13.6	295	254	292	269	278	301	BARLEY,10 INCH
L17	13.7	288	279	305	274	293	314	BARE,CULTIVATED
L16	13.9	287	282	304	274	286	311	BARE,CULTIVATED
L39	13.9	294	281	289	274	288	313	BARE,CULTIVATED
L50	17.2	293	277	290	273	283	308	YOUNG BARLEY,SPARSE
L49	19.0	292	273	289	272	287	309	BARE,CULTIVATED
L43	20.6	293	268	290	271	284	310	YOUNG BARLEY,SPARSE
L42	21.5	293	274	301	273	289	310	BARE,MELONS
L40	21.9	294	263	284	271	283	306	YOUNG BARLEY,SPARSE
L02	22.2	290	243	297	262	280	303	ALFALFA,12 INCH
L19	22.8	291	270	300	261	278	302	OLD LETTUCE,NOT CULT
L38	23.0	293	206	218	213	238	277	BARE,CULTIVATED
L21	24.0	294	271	303	270	287	309	BARE,IN COTTON
L20	24.5	293	278	295	271	287	310	BARE,IN COTTON
L48	24.5	294	215	233	216	241	277	BARE,CULTIVATED
L18	24.9	290	266	306	261	280	303	OLD LETTUCE,NOT CULT
L46	25.4	292	261	290	268	286	306	BARE,IN COTTON
L41	26.3	294	253	277	260	276	303	YOUNG BARLEY,SPARSE
L45	27.6	292	260	296	270	287	310	BARE,IN COTTON
L30	28.2	294	248	288	269	283	306	ALFALFA,5 INCH
L06	30.8	295	262	287	254	283	307	BARE,IN COTTON
L47	31.2	293	208	225	208	234	271	BARE,CULTIVATED
L03	35.4	291	231	260	228	251	285	BARE,WATER IN FIELD
L05	36.1	288	227	258	241	265	294	BARE,IN COTTON
L04	37.0	288	219	253	242	266	295	BARE,IN COTTON

LINEAR REGRESSION RESULTS

INTERCEPT	290.0	307.8	286.4	292.0	315.5	DEGREES KELVIN
SLOPE	-1.54	-1.17	-1.24	-0.72	-0.61	DEGREES K/% SOIL MOISTURE
STD ERR OF ESTIMATE	18.8	22.0	16.8	14.8	10.1	DEGREES KELVIN
CORRELATION	0.589	0.430	0.549	0.400	0.472	COEFFICIENT

Table 6

BRIGHTNESS TEMP RESULTS FROM ...PHOENIX, ARIZONA FLIGHT NO. 1

DATE FEB. 25 ,1971 TIME 16:57 TO 17:11 LST

FIELD NO	SOIL MOIST	IR TEMP	WAVELENGTH IN CM 21.1	6.01	1.55	0.8H	0.8V	FIELD CONDITIONS
160	3.2	292	273	300	276	288	311	BARE,FLAT
105	3.3	297	271	288	273	290	311	BARE,FURROWED
107	4.2	296	271	304	273	285	310	BARE,PLOWED
150	4.6	297	265	302	271	283	308	BARE,PLOWED
153	4.9	293	271	295	267	278	307	BARE,LAND PLANED
154	5.5	296	263	289	265	280	309	BARE,LAND PLANED
123	5.5	295	271	299	272	285	309	BARE,PLOWED
119	5.6	296	276	298	274	288	311	BARE,DISKED
116	5.7	293	268	302	274	289	312	BARE,FURROWED
121	5.9	291	256	296	274	290	309	PLOWED
35	5.9	293	255	298	276	281	305	BARE,FLOATED
100	6.1	295	258	306	275	285	310	BARE,PLOWED
59	6.6	293	271	305	274	288	310	BARE,FURROWED
17	6.7	295	273	298	275	286	310	BARE,DEEP PLOWED
16	6.9	295	265	297	275	287	309	BARE,PLOWED
32	7.7	295	270	296	275	285	309	BARE,LAND PLANED
159	7.9	290	265	294	266	282	309	SAFFLOWER SEEDLINGS
125	8.0	291	275	292	273	283	309	BARE,DISKED
146	11.9	297	248	287	260	271	304	BARE,FLAT
120	14.6	292	257	284	267	282	305	WHEAT,6 INCH
37	18.3	296	249	295	266	282	309	YOUNG ALFALFA
179	18.8	296	243	278	259	273	305	ALFALFA,SPROUTING
46	19.0	292	264	292	265	279	301	BEETS,FURROWS
25	20.1	295	239	277	251	278	306	BARE,FURROWED
24	21.3	296	236	281	259	277	305	BARE,FURROWED
97	21.5	294	229	268	248	270	295	ALFALFA,10 INCH
85	25.0	290	220	257	237	248	285	BARE,FLAT,IRR-2/22
80	25.7	296	221	264	243	259	290	BARE,FLAT,IRR-2/21

LINEAR REGRESSION RESULTS

	21.1	6.01	1.55	0.8H	0.8V	
INTERCEPT	279.4	306.5	280.4	291.4	313.8	DEGREES KELVIN
SLOPE	-2.00	-1.46	-1.30	-1.02	-0.71	DEGREES K/% SOIL MOISTURE
STD ERR OF ESTIMATE	7.8	6.7	5.1	5.9	3.9	DEGREES KELVIN
CORRELATION	0.883	0.849	0.884	0.789	0.803	COEFFICIENT

BRIGHTNESS TEMP RESULTS FROM ...PHOENIX, ARIZONA   FLIGHT NO. 3

DATE MAR. 01 ,1971   TIME 13:34 TO 13:45 LST

FIELD NO	SOIL MOIST	IR TEMP	WAVELENGTH IN CM 21.1	6.01	1.55	0.8H	0.8V	FIELD CONDITIONS
160	1.6	287	260	280	263	275	295	BARE,FURROWED
105	3.2	295	265	295	267	281	300	BARE,FURROWED
141	4.3	295	263	290	267	278	299	BARE,DISKED
159	4.7	292	259	283	256	274	294	SAFFLOWER SEEDLINGS
107	3.5	295	258	285	264	281	300	BARE,PLOWED
123	5.5	293	271	290	267	278	300	BARE,VERY CLODDY
119	5.6	291	262	290	268	277	300	BARE,FURROWED
116	5.7	291	264	286	268	278	299	BARE,FURROWED
48	5.9	288	266	286	265	280	300	BARE,VERY CLODDY
100	6.0	290	262	294	268	280	301	BARE,FLAT
144	6.1	294	267	280	265	276	299	BARE,PLOWED
61	6.7	294	250	284	267	277	297	BARE,FURROWED
125	7.6	289	261	278	269	280	302	BARE,DISKED
174	8.4	285	257	275	262	274	296	BARE,FLAT
62	8.7	288	257	286	270	280	301	BARE,FURROWED
201	8.7	288	263	284	265	276	298	BARE,FLAT
121	10.2	291	254	283	269	278	300	BARE,CLODDY
183	13.9	288	249	276	257	270	293	ALFALFA SEEDLINGS
181	14.9	287	249	262	256	270	293	ALFALFA SEEDLINGS
71	17.2	294	243	286	271	274	299	BARE,FLAT,DRY ON TOP
97	20.0	284	230	271	261	276	296	ALFALFA,10 INCH
38	21.5	287	221	243	214	263	288	BARE,FLAT
120	22.5	290	256	276	264	273	294	WHEAT,6INCH
85	23.0	293	240	266	261	275	297	BARE,FLAT
80	23.1	291	235	280	262	275	296	BARE,FLAT
56	25.0	289	219	252	246	272	294	BARE,FURROWED
63	27.0	290	234	255	255	274	295	BARE,FURROWED
53	29.1	285	222	256	226	268	292	BARE,FLAT

LINEAR REGRESSION RESULTS

	21.1	6.01	1.55	0.8H	0.8V	
INTERCEPT	270.3	292.6	271.3	279.4	300.0	DEGREES KELVIN
SLOPE	-1.56	-1.24	-0.90	-0.32	-0.24	DEGREES K/% SOIL MOISTURE
STD ERR OF ESTIMATE	7.4	8.4	10.6	3.2	2.7	DEGREES KELVIN
CORRELATION	0.877	0.785	0.587	0.654	0.615	COEFFICIENT

Table 8

BRIGHTNESS TEMP RESULTS FROM ...WESLACO, TEXAS   FLIGHT NO. 3

DATE MAR. 01 .1971   TIME 16:50 TO 17: 0 LST

FIELD NO	SOIL MOIST	IR TEMP	WAVELENGTH IN CM 21.1	6.01	1.55	0.8H	0.8V	FIELD CONDITIONS
117	****	311	250	284	276	311	293	LIGHT VEGETATION
138	****	305	283	307	285	302	325	BARE
148	****	306	239	266	262	285	304	ONIONS,IRR. 2/24
104	6.7	307	288	311	287	305	326	BARE,LARGE CLODS
79	7.8	304	278	314	285	301	322	BARE,LARGE CLODS
111	8.5	305	285	316	286	304	324	BARE,FLAT,SMALL CLOD
113	10.1	308	282	310	288	301	324	BARE,MEDIUM CLODS
122	13.5	307	274	306	283	303	322	BARE,SMALL CLODS
107	14.1	307	276	313	286	301	322	BARE,SMALL CLODS
116	16.0	311	288	306	286	304	325	BARE,SMALL CLODS
105	22.3	307	240	291	277	297	317	BARE,SMALL CLODS
109	35.0	305	245	266	246	285	300	BARE,IRRIGATED
120A	35.0	307	225	258	247	282	299	BARE,SMALL CLODS
120B	35.0	308	240	271	256	282	298	BARE,SMALL CLODS

LINEAR REGRESSION RESU_TS

INTERCEPT	299.7	330.5	301.2	311.0	334.0	DEGREES KELVIN
SLOPE	-1.84	-1.83	-1.41	-0.76	-0.95	DEGREES K/% SOIL MOISTURE
STD ERR OF ESTIMATE	10.3	5.3	5.5	2.9	3.3	DEGREES KELVIN
CORRELATION	0.907	0.973	0.951	0.954	0.961	COEFFICIENT

Below each table are the results of a linear regression analysis performed on the brightness temperature - soil moisture data in that table. In general, the correlation coefficient decreases with decreasing wavelength as do the slopes of the curves, indicating a greater sensitivity to soil moisture with the longer wavelength radiometers. This result is in agreement with the ground based measurements of Poe, et al. (1971).

The results from Weslaco on March 1 and Phoenix on February 25 yielded the strongest correlation with soil moistures while the two passes over the Imperial Valley yielded the poorest correlations. This is not due to any soil differences since the range of soil textures in the Imperial Valley is essentially the same as those in the Phoenix area. A closer look at the 21.1 cm data in Figure 3 from the Imperial Valley, shows little or no variation in the brightness temperatures for soil moistures up to about 20%. Above 20% they decrease rather rapidly, i.e. $\simeq 3°/\%$ soil moisture. This effect was also observed at 1.55 cm for all three test sites and will be discussed more fully below. This non-linear behavior is the cause of the low values for the linear coorelation coefficient.

The results from the 21.1 cm radiometer for the two flights over the Phoenix area are shown in Figure 4. Brightness temperatures are plotted versus the average soil moisture in a 15 cm sample. The solid line is the linear regression fit to the data for the flight on February 25 and the dashed line is for the data from the flight on March 1. The standard deviation of the data from the line is about 8°K in both cases. It is apparent that the brightness temperatures of the dry fields were about 10°K lower on the March 1 flight while the wet fields are at about the same temperatures. On the other hand, the surface temperatures of the dry fields were only about 2-5°C cooler for the March 1 flight. This decrease only partially accounts for the difference in the radiometric temperatures. This phenomenon may be understood on the following basis. In dry fields, the skin depth is several wavelengths* and the radiometers receive radiation from the sub-surface layers. The difference then is due to thermal gradients in the soil on March 1. The flight time (5:00 P.M.) on February 25, was chosen so that the temperature profile was approximately constant. A flight time near midday was chosen on March 1 to maximize the thermal gradient in the soil. These times were determined for us by Dr. Ray Jackson of the U.S. Water Conservation Laboratory at Phoenix, Arizona. Thus both the sub-surface layers and surface layer were cooler for the March 1 flight. The wet fields would not have been affected because their greater heat capacity minimizes temperature fluctuations and the skin depth in the wet soil is much less.*

*These skin depths were calculated using the dielectric constants measured by Geiger (1972).

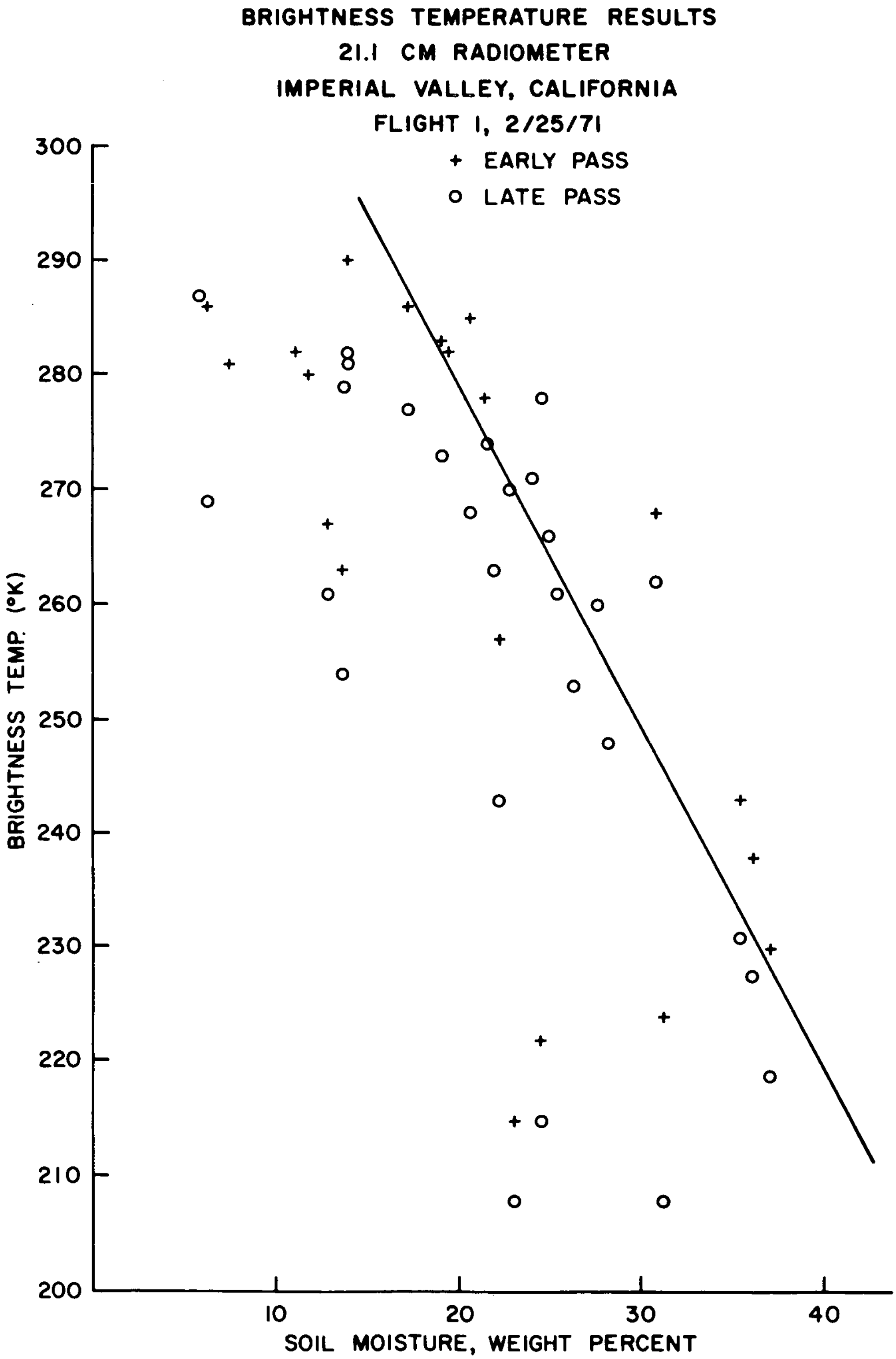

Figure 3. Plot of 21.1 cm Brightness Temperature vs Soil Moisture from the Imperial Valley

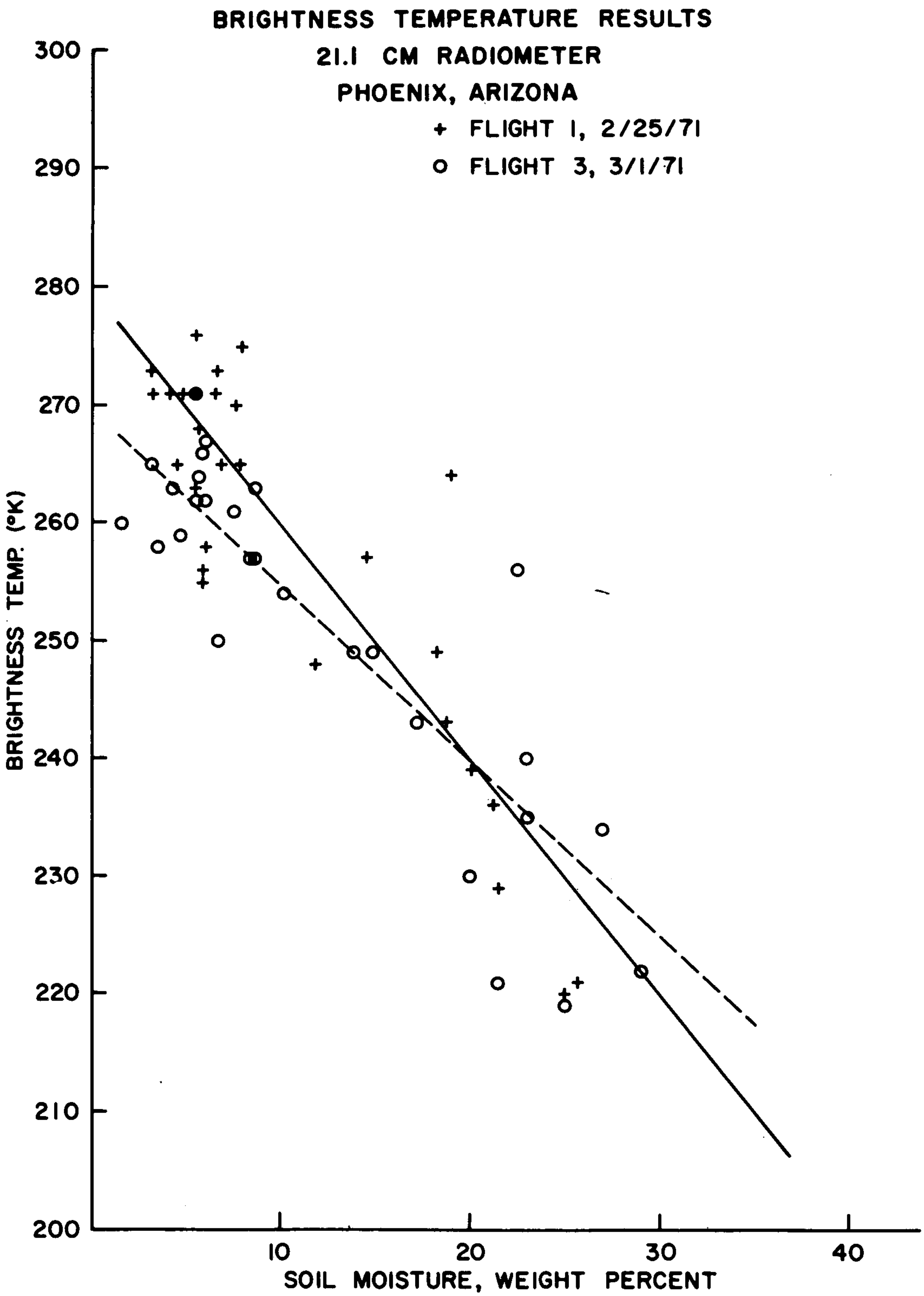

Figure 4. Plot of 21.1 cm Brightness Temperatures vs Soil Moisture from Phoenix, Arizona

The range of brightness temperature differences ($\simeq$50-60°K) observed in the aircraft measurements over Phoenix were only about one half those observed in the ground-based measurements of change throughout Poe, et al. (1971) for the same range of soil moistures. At an altitude of 0.9km, the atmospheric effects are small and cannot account for this difference. The difference then is due to surface effects, primarily roughness and thermometric temperature. Poe's measurements were made on a smooth field in July when the surface temperatures were 10-20°K warmer than those observed for our measurements. The dry fields in July would appear that much warmer while there would be only about half that difference for the wet fields. The rougher surfaces of the plowed and furrowed wet fields observed during aircraft measurements appear to have higher emissivities, than the smooth, wet field studied by Poe et al., also accounting for the smaller difference between wet and dry fields observed by us.

It is interesting to note that the range of temperatures for the 1.55cm radiometer was only slightly smaller than those for the longer wavelength radiometers, which is encouraging for the potential use in large area soil moisture sensing with the 1.55cm electrically scanning radiometer scheduled to be on Nimbus V.

OFF-NADIR 1.55cm RESULTS

As noted in Table 1, the 1.55cm radiometer on board the aircraft is a scanning radiometer. The scan is perpendicular to the flight path and the amplitude is ±50°. Thus the radiation from a swath whose width is approximately twice the aircraft altitude is mapped. Figure 5 is a false-color image of a pass over a south to north leg 8 km west of the city of Phoenix. At the speed of 250 knots and altitude of 0.9 km above ground level, adjacent scans are not contiguous and the resulting image is compressed longitudinally by a factor of 3. Nevertheless, the rectangular nature of the fields is apparent and we are clearly able to distinguish between wet and dry fields.

The brightness temperatures of the target fields are presented in Tables 9, 10, and 11, for the Imperial Valley, Phoenix, and Weslaco, respectively. The look angles in Tables 9 and 10 are the angles from nadir to the field centers.

As a consequence of scanning, a larger data base was obtained from which it was possible to extract some additional results that were not apparent in the multi-frequency data. These are: 1) the non-linear dependence of the microwave emission on soil moisture content, 2) the effect of surface roughness in decreasing the sensitivity to soil moisture, and 3) the decreased sensitivity at large viewing angles (i.e., > 22°).

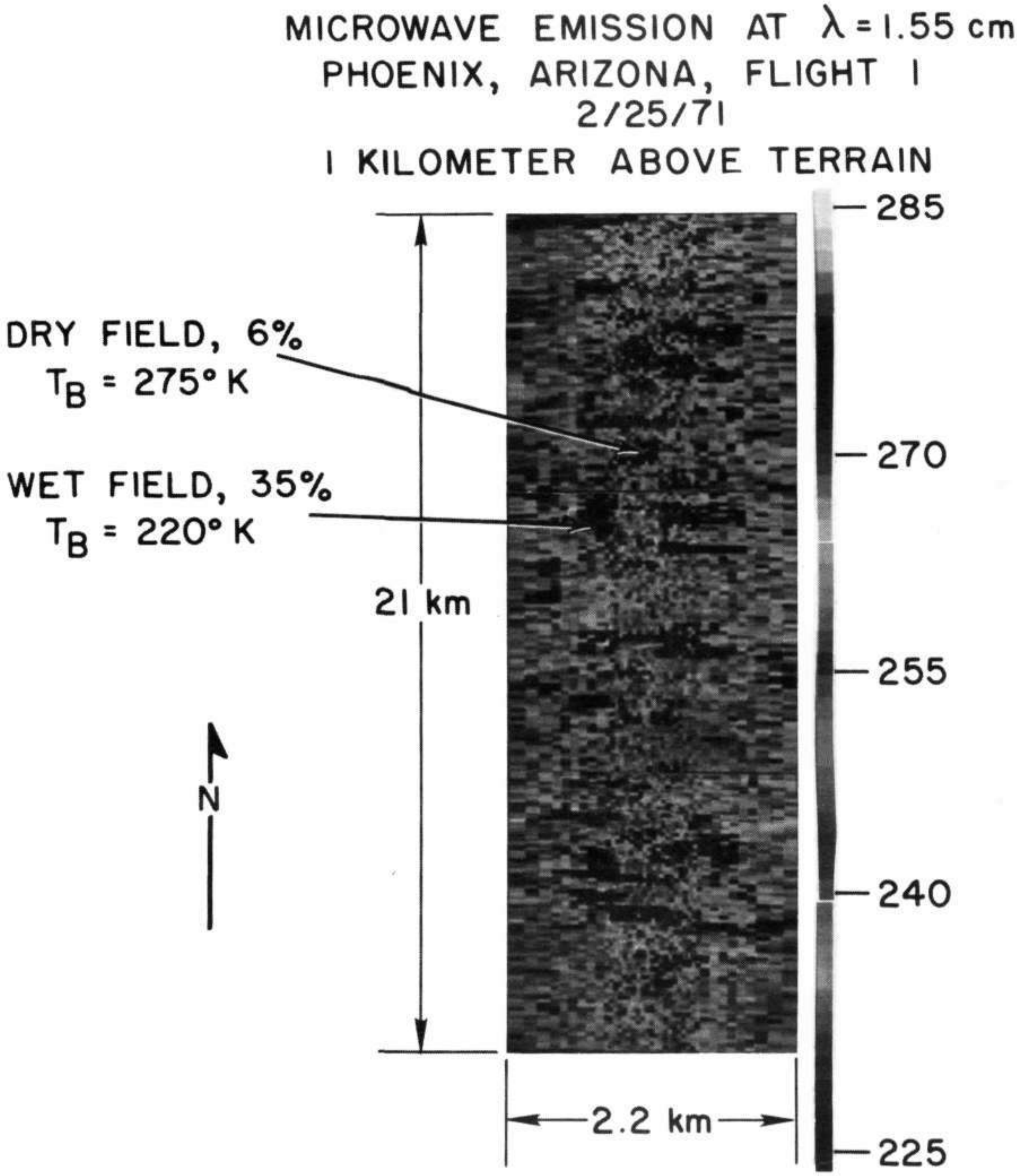

Figure 5. False color 1.55 cm Microwave Image of a South to North Track 5 miles West of Phoenix, Arizona.

Table 9

BRIGHTNESS TEMPERATURE RESULTS FROM THE IMPERIAL VALLEY AT 1.55 CM
FLIGHT 1 - FEBRUARY 25, 1971

FIELD NO	% SOIL MOISTURE	EARLY PASS BTE	EARLY PASS LOOK ANGLE	LATE PASS BTL	LATE PASS LOOK ANGLE	FIELD CONDITIONS
1	3.0	271	-9.2	268	-2.3	BARE,FALLOW,LT BRUSH
2	22.2	262	0.0	262	-2.3	ALFALFA, 12 INCH
3	35.4	227	-6.9	228	-2.3	BARE,WATER IN FIELD
4	37.0	238	2.3	242	4.6	BARE,PLANTED IN COTTON
5	36.1	241	-2.3	241	0.0	BARE,PLANTED IN COTTON
6	30.8	252	4.6	254	4.6	BARE,PLANTED IN COTTON
7	4.4	259	0.0	254	-4.6	BARE,CALIPATRIA AIRPORT
8	6.5	259	0.0	253	-4.6	BARE,CALIPATRIA AIRPORT
9	21.4	274	2.3	272	-11.5	BARE,PLANTED IN COTTON
10	19.4	277	2.3	272	-11.5	BARE,PLANTED IN COTTON
11	7.4	282	2.3	274	-11.5	BARE,CULTIVATED
12	7.4	282	0.0	274	-11.5	BARE,CULTIVATED
13	11.1	283	9.2	273	-18.6	BARE,CULTIVATED
14	11.7	283	9.2	273	-18.6	BARE,CULTIVATED
15	22.5	256	11.5	255	-18.6	SUGAR BEETS,24 INCH
16	13.9	282	16.2	274	-9.2	BARE,CULTIVATED
17	13.7	283	16.2	274	-9.2	BARE,CULTIVATED
18	24.9	267	21.0	261	-6.9	OLD LETTUCE,NOT CULT
19	22.8	263	21.0	261	-6.9	OLD LETTUCE,NOT CULT
20	24.5	276	18.6	271	6.9	BARE,PLANTED IN COTTON
21	24.0	278	18.6	270	6.9	BARE,PLANTED IN COTTON
22	31.5	241	21.0	246	11.5	BARE,WATER IN FIELD
23	31.6	250	18.6	251	11.5	BARE,PLANTED IN MELONS
24	7.9	270	18.6	267	9.2	BARE,CULTIVATED
25	28.7	269	9.2	267	6.9	NOT CULT.LT.BRUSH
26	33.2	267	21.0	266	13.8	BARE,PLANTED IN COTTON
27	36.2	261	21.0	263	13.8	BARE,PLANTED IN COTTON
28	31.8	275	13.8	271	11.5	BARE,PLANTED IN COTTON
29	27.7	276	13.8	272	11.5	BARE,PLANTED IN COTTON
30	28.2	269	13.8	269	6.9	ALFALFA,3-5 INCH
31	14.5	266	11.5	265	4.6	BARE,NOT CULT
32	18.8	266	11.5	261	4.6	BARE,NOT CULT
33	22.2	264	11.5	267	0.0	BARE,NOT CULT
34	9.3	270	11.5	263	0.0	BARE,NOT CULT
35	13.6	267	0.0	269	-4.6	BARLEY,8-10 INCH
36	6.2	279	6.9	273	4.6	BARE,CULT,ODD SHAPED
37	5.7	279	-2.3	272	6.9	BARE,CULT,ODD SHAPED
38	23.0	206	2.3	213	-6.9	BARE,CULTIVATED
39	13.9	282	2.3	274	-11.5	BARE,CULTIVATED
40	22.0	271	18.6	271	-4.6	YOUNG BARLEY, SPARSE
41	26.3	259	18.6	260	-4.6	YOUNG BARLEY, SPARSE
42	21.5	276	18.6	273	-4.6	BARE,PLANTED IN MELONS
43	20.6	273	4.6	271	-11.5	YOUNG BARLEY,SPARSE
44	12.8	272	2.3	272	-11.5	ALFALFA,12 INCH
45	27.7	270	11.5	270	0.0	BARE,PLANTED IN COTTON
46	25.4	271	11.5	268	0.0	BARE,PLANTED IN COTTON
47	31.2	200	2.3	208	-6.9	BARE,CULTIVATED
48	24.5	209	2.3	216	-6.9	BARE,CULTIVATED
49	19.0	273	2.3	272	-6.9	BARE,CULTIVATED
50	17.2	275	2.3	272	-6.9	YOUNG BARLEY SPARSE

BTE - DATA FROM EARLY PASS(14:30-15:00 PST) AT AN ALTITUDE OF 0.9 KM
BTL - DATA FROM LATE PASS (17:00-17:30 PST) AT AN ALTITUDE OF 0.9 KM

Table 10

BRIGHTNESS TEMPERATURE RESULTS FROM PHOENIX AT 1.55 CM
FLIGHT 1 - FEB. 25,1971 FLIGHT 3 - MAR. 1,1971

	FLIGHT 1 RESULTS			FLIGHT 3 RESULTS			
FIELD NO	BT1	% SOIL MOISTURE	LOOK ANGLE	BT3	% SOIL MOISTURE	LOOK ANGLE	FIELD CONDITIONS
1	245	14.6	-45.9	260	16.9	-31.2	BARE,FURROWED
2	256	16.0	-45.9	258	14.1	-31.2	BARE,FURROWED
3	265	8.2	-42.7	264	7.8	-26.0	BARE,FEW WEEDS
4	233	25.0	-42.7	254	16.2	-28.6	BARE,FURROWED
6	268	5.8	-31.2	264	4.3	-11.5	BARE,FLOATED>FURROWS
7	270	5.9	-31.2	230	14.7	-11.5	BARE,FLOATED>FURROWS
8	276	5.6	-31.2	268	3.7	-11.5	BARE,FLOATED>FURROWS
9	276	6.0	-13.8	269	4.6	11.5	BARE,FURROWED
11	255	15.3	-31.2	264	12.7	-11.5	BARE,FURROWED
12	265	13.4	-31.2	266	10.9	-11.5	BARE,FURROWED
13	271	4.3	-31.2	269	4.1	-11.5	BARE,FURROWED,CLODDY
14	272	14.4	-11.5	266	13.9	6.9	BARE,FURROWED
15	269	6.8	-11.5	267	6.0	6.9	BARE,FURROWED
16	275	6.9	6.9	266	6.0	28.6	BARE,PLOWED,CLODDY
17	275	6.7	6.9	265	6.0	26.0	BARE,RIPPED
18	253	35.0	26.0	247	****	42.7	BARE,AT FIELD CAP
19	239	35.0	26.0	249	****	42.7	BARE,AT FIELD CAP
20	270	23.2	26.0	262	****	42.7	BARE,FURROWED
21	261	21.4	26.0	251	****	42.7	BARE,FURROWED
23	270	7.1	26.0	251	6.5	42.7	BARE,FLOATED
24	259	21.3	6.9	259	18.4	26.0	BARE,FURROWED
25	251	20.1	6.9	259	16.8	26.0	BARE,FURROWED
26	271	5.8	23.5	238	****	42.7	BARE,WET HALF=235
27	274	4.4	23.5	232	****	42.7	BARE,FURROWED,CLODDY
28	269	19.0	-31.2	268	17.2	-11.5	BARE,FURROWED
29	***	4.8	*****	258	****	-28.6	BARE,FLAT
30	***	4.5	*****	230	18.3	-28.6	BARE,FLAT&ROCKY
31	269	7.2	-31.2	263	5.8	-13.8	BARE,FLOATED
32	275	7.7	6.9	261	6.5	28.6	BARE,FLOATED
33	266	13.6	26.0	255	****	42.7	BARE,FURROWED
34	264	15.8	26.0	255	****	42.7	BARE,FURROWED
35	276	5.9	6.9	264	5.0	28.6	BARE,FLOATED
36	265	4.8	26.0	251	****	42.7	BARE,FURROWED
37	266	18.3	19.6	257	****	28.6	ALFALFA,GOOD STAND
38	274	8.5	-13.8	214	21.5	11.5	BARE,FLAT
39	***	4.8	*****	261	4.4	-31.2	BARE,VERY CLODDY
42	270	14.7	26.0	259	****	42.7	BARE,FURROWED
43	274	13.5	26.0	260	****	42.7	BARE,FURROWED
44	223	35.0	26.0	244	26.6	42.7	BARE,AT FIELD CAP
45	214	35.0	26.0	246	****	42.7	BARE,AT FIELD CAP
46	265	19.0	6.9	257	****	26.0	BEETS,FURROWS
47	268	8.7	-31.2	258	****	-16.2	BARE,FLOATED

BT1 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 1 AT 17:00 MST
BT3 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 3 AT 13:40 MST.

Table 10 (continued)

BRIGHTNESS TEMPERATURE RESULTS FROM PHOENIX AT 1.55 CM
FLIGHT 1 - FEB. 25, 1971   FLIGHT 3 - MAR. 1, 1971

	FLIGHT 1 RESULTS			FLIGHT 3 RESULTS			
FIELD NO	BT1	% SOIL MOISTURE	LOOK ANGLE	BT3	% SOIL MOISTURE	LOOK ANGLE	FIELD CONDITIONS
48	276	6.9	-13.8	265	5.9	6.9	BARE, VERY CLODDY
49	276	8.0	-31.2	265	6.7	-13.8	BARE, VERY CLODDY
52	199	32.8	-26.0	244	29.0	-16.2	BARE, FLAT, IRR-2/25
53	201	32.8	-9.2	226	29.1	6.9	BARE, FLAT, IRR-2/25
55	247	25.9	-26.0	250	23.6	-16.2	BARE, FURR., IRR-2/24
56	245	27.5	-9.2	246	24.0	6.9	BARE, FURR., IRR-2/24
57	275	6.7	31.2	***	****	*****	BARE, FURROWED
58	274	7.6	26.0	***	****	*****	BARE, FURROWED
59	274	6.6	21.0	265	6.6	31.2	BARE, FURROWED
60	239	24.1	11.5	251	24.9	28.6	BARE, FURR., IRR-2/24
61	275	6.7	-11.5	267	6.0	4.6	BARE, FURROWED
62	277	8.7	-11.5	270	7.0	6.9	BARE, FURROWED
63	242	27.7	-9.2	255	****	6.9	BARE, FURROWED
64	273	6.5	-28.6	268	6.7	-16.2	BARE, FURROWED
65	250	21.2	-28.6	258	22.4	-16.2	BARE, FURROWED
66	***	6.3	*****	266	7.1	-33.9	BARE, FURROWED
70	***	9.2	*****	267	****	-33.9	BARE, FLAT
71	273	16.7	-9.2	271	17.2	6.9	BARE, FLAT&DRY
72	258	13.5	-42.7	267	9.8	-33.9	BARE, PLOWED
73	257	20.0	-26.0	258	****	-16.2	BARLEY, LUSH-6 INCH
74	260	18.3	-26.0	253	16.8	-16.2	SUGAR BEETS, 12 INCH
75	228	31.4	26.0	254	****	45.9	BARE, FLAT
76	235	28.6	9.2	260	****	28.6	BARE, FLAT, WET ON TOP
77	252	29.0	-9.2	263	****	6.9	BARE, FLAT, DRY ON TOP
78	259	28.4	-26.0	264	20.2	-16.2	BARE, FLAT, DRY ON TOP
79	268	21.5	26.0	260	****	45.9	ALFALFA, 10 INCH, LUSH
80	243	25.7	2.3	262	23.1	6.9	BARE, FLAT, IRR-2/21
81	225	25.7	21.0	252	22.3	28.6	BARE, FLAT, IRR-2/24
82	232	26.0	39.6	248	23.4	45.9	BARE, FLAT, IRR-2/24
83	245	24.3	42.7	255	18.8	45.9	BARE, FLAT
84	256	22.3	26.0	260	17.9	23.6	BARE, FLAT, IRR-2/22
85	237	25.2	6.9	261	****	6.9	BARE, FLAT, IRR-2/22
86	261	18.3	-16.2	261	****	-16.2	BARLEY, 12 INCH LUSH
89	271	17.6	-16.2	264	****	-16.2	WHEAT, 12 INCH, LUSH
90	227	25.8	23.5	234	****	26.0	BARE, FURR., IRR-2/25
91	267	5.3	39.6	246	****	45.9	BARE, FURROWED
92	265	4.4	39.6	259	4.1	45.9	BARE, LAND, PLANED
93	273	5.1	23.5	266	5.0	26.0	BARE, FURROWED
94	275	3.4	23.5	266	3.4	26.0	BARE, FURROWED
95	264	3.0	39.6	259	****	42.7	BARE, FURROWED
96	259	12.2	39.6	250	7.7	42.7	SAFFLOWER, 1 INCH

BT1 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 1 AT 17:00 MST
BT3 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 3 AT 13:40 MST.

Table 10 (continued)

BRIGHTNESS TEMPERATURE RESULTS FROM PHOENIX AT 1.55 CM
FLIGHT 1 - FEB. 25,1971 FLIGHT 3 - MAR. 1,1971

	FLIGHT 1 RESULTS			FLIGHT 3 RESULTS			
FIELD NO	BT1	% SOIL MOISTURE	LOOK ANGLE	BT3	% SOIL MOISTURE	LOOK ANGLE	FIELD CONDITIONS
97	248	21.5	0.0	261	****	2.3	ALFALFA,10 INCH
98	221	25.5	23.5	236	19.7	23.5	BARE,FURR.,IRR-2/25
99	270	6.8	23.5	266	****	21.0	BARE,FLAT,MANURE
100	275	6.1	0.0	268	5.0	-2.3	BARE,LAND PLANED
104	268	3.6	-23.5	266	3.5	-16.2	BARE,FURROWED
105	273	3.3	-2.3	267	3.2	6.9	BARE,FURROWED
107	273	4.2	-2.3	264	3.5	6.9	BARE,PLOWED
108	273	3.6	18.6	264	2.5	26.0	BARE,FURROWED
109	271	3.3	36.7	***	2.6	*****	BARE,FURROWED
110	270	8.4	18.6	264	****	26.0	BARLEY,6 INCH
112	269	3.0	19.6	260	4.4	26.0	BARE,VERY CLODDY
114	267	4.6	-39.6	265	****	-33.9	BARE,PLOWED &DISKED
115	269	6.3	-18.6	265	5.0	-13.8	BARE,MAIZE STUBBLE
116	274	5.7	2.3	268	5.0	6.9	BARE,FURROWED
117	269	10.2	23.5	263	****	26.0	OATS,6 INCH
118	269	6.0	-18.6	267	5.0	-13.8	BARE,PLOWED&DISKED
119	274	5.6	2.3	268	5.0	6.9	BARE,PLOWED&DISKED
120	267	14.6	2.3	264	22.5	6.9	WHEAT,6 INCH
121	274	5.9	2.3	269	10.2	6.9	BARE,CLODDY
122	273	3.9	-18.6	270	4.1	-16.2	BARE,ROUGH PLOWED
123	272	5.5	2.3	267	5.0	6.9	BARE,VERY CLODDY
124	269	6.4	-16.2	266	6.1	-16.2	BARE,PLOWED&DISKED
125	273	7.6	6.9	269	5.0	6.9	BARE,PLOWED&DISKED
126	268	5.9	28.6	268	5.0	31.2	BARE,PLOWED&DISKED
128	267	5.1	28.6	265	4.6	28.6	BARE,PLOWED&DISKED
131	262	5.8	-31.2	256	****	-33.9	BARE,FLOATED
132	269	7.3	28.6	263	4.5	26.0	BARE,ROUGH PLOWED
135	268	4.8	-31.2	266	4.0	-33.9	BARE,PLOWED&DISKED
235	267	9.7	-9.2	264	7.3	-16.2	ALFALFA,6 INCH,135A
136	267	4.8	28.6	261	4.0	26.0	BARE,PLOWED
139	272	4.9	-31.2	267	4.0	-31.2	BARE,PLOWED&DISKED
140	273	9.7	-9.2	267	6.9	-16.2	BARE,LAND PLANED
141	276	6.3	9.2	267	4.3	4.6	BARE,DISKED
142	269	8.0	-31.2	245	11.4	-33.9	BARLEY,4 INCH
143	275	4.6	-9.2	262	3.9	-16.2	BARE,LAND PLANED
144	274	6.1	9.2	265	5.5	4.6	BARE,PLOWED
146	260	11.9	-4.6	213	18.0	-16.2	BARE,FLAT,IRR-2/27
147	274	4.5	-26.0	260	4.6	-39.6	BARE,FURROWED
149	274	4.9	-28.6	263	4.8	-39.6	BARE,LISTED
150	271	4.6	-6.9	260	4.0	-16.2	BARE,VERY CLODDY
151	260	4.8	-28.6	249	****	-39.6	BARE,PLANED,CLODS

BT1 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 1 AT 17:00 MST
BT3 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 3 AT 13:40 MST.

Table 10 (continued)

BRIGHTNESS TEMPERATURE RESULTS FROM PHOENIX AT 1.55 CM

FLIGHT 1 - FEB. 25,1971 FLIGHT 3 - MAR. 1,1971

	FLIGHT 1 RESULTS			FLIGHT 3 RESULTS			
FIELD NO	BT1	% SOIL MOISTURE	LOOK ANGLE	BT3	% SOIL MOISTURE	LOOK ANGLE	FIELD CONDITIONS
153	267	4.9	-6.9	255	4.3	-16.2	BARE,LAND PLANED
154	265	5.5	-6.9	255	3.7	-16.2	BARE,LAND PLANED
156	275	3.3	-42.7	265	1.5	-36.7	BARE,CLODDY
158	268	6.6	-23.5	263	****	-18.6	ALFALFA,6 INCH
159	266	7.9	0.0	256	4.7	4.6	SAFFLOWER,SEEDLINGS
160	276	3.2	0.0	263	1.6	4.6	BARE,FLAT>FURROWED
161	265	1.9	23.5	258	1.6	26.0	BARE,FURROWED
163	276	5.3	23.5	264	4.1	28.6	BARE,FURROWED
165	271	[illegible]	23.5	261	3.2	26.0	BARE,FURROWED
167	268	10.3	23.5	257	10.5	26.0	BARE,FLAT
168	271	11.7	-23.5	256	11.3	-18.6	BARLEY, 10 INCH
169	263	15.1	-23.5	260	****	-19.6	BARLEY, 10 INCH
171	254	20.9	-23.5	252	18.1	-18.6	ALFALFA,6 INCH
172	262	19.1	23.5	259	****	28.6	ALFALFA,6 INCH
173	273	9.0	-11.5	261	8.5	-13.6	BARE,FLAT
174	274	8.4	11.5	262	7.0	4.6	BARE,FLAT
175	271	8.3	-21.0	***	****	*****	BARE,FLAT
177	263	7.4	-31.2	***	****	*****	BARE,FLAT
178	267	6.9	-9.2	***	7.1	*****	BARE,FLAT
179	259	18.8	9.2	247	****	-33.9	ALFALFA,SEEDLINGS
180	275	5.1	16.2	261	4.5	-13.8	BARE,VERY CLODDY
181	265	20.1	13.8	256	14.9	-13.8	ALFALFA,SEEDLINGS
182	263	22.1	13.8	257	****	-13.8	ALFALFA,SEEDLINGS
183	261	20.0	33.9	256	13.9	11.5	ALFALFA,SEEDLINGS
184	262	23.6	33.9	257	****	11.5	ALFALFA,SEEDLINGS
185	***	23.0	*****	252	15.0	33.9	ALFALFA,SEEDLINGS
186	***	24.0	*****	249	17.9	33.9	ALFALFA,SEEDLINGS
188	***	21.9	*****	254	****	33.9	ALFALFA,SEEDLINGS
189	***	4.1	*****	263	3.3	33.9	BARE,FURROWED
193	***	5.5	*****	263	4.0	33.9	BARE,FURROWED
194	***	7.8	*****	261	5.0	33.9	BARE,FURROWED
197	***	8.4	*****	260	5.0	26.0	BARE,CLODDY,FLAT
198	272	7.9	19.6	260	3.5	-21.0	BARE,SMOOTH&FLAT
199	273	8.4	-18.6	***	****	*****	BARE,FLAT CLODDY
200	***	6.1	*****	264	3.0	23.5	BARE,CLODDY,FURROWS
201	273	8.7	39.6	265	4.0	2.3	BARE,FLAT
202	269	7.8	39.6	262	4.0	2.3	BARE,FLAT
203	***	9.2	*****	263	4.6	26.0	BARE,SMOOTH>FURROWS
205	245	22.3	19.6	254	16.1	-21.0	ALFALFA,2LEAF STAGE

BT1 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 1 AT 17:00 MST

BT3 - DATA FROM LOW ALTITUDE (0.9 KM) PASS DURING FLIGHT 3 AT 13:40 MST.

Table 11

BRIGHTNESS TEMPERATURE RESULTS FROM WESLACO ,TEXAS AT 1.55 CM
FLIGHT 3 - MARCH 1,1971 FLIGHT 4 - MARCH 2,1971

FIELD NO	% SOIL MOISTURE 1-3 CM	15 CM	FLIGHT 3 RESULTS IR	BT	FLIGHT 4 RESULTS IR	BT	FIELD CONDITIONS
55	44.3	39.5	297	248	302	247	CABBAGE,SPARSE
57	15.7	23.3	302	277	312	292	CORN SEEDLINGS
59	13.8	21.7	305	278	316	300	BARE,BURROWED SM CLD
61	28.1	28.1	302	281	312	296	BARE,BURROWED SM CLD
63	23.5	28.7	303	284	311	293	BARE,BURROWED SM CLD
79	7.8	13.6	308	285	316	299	BARE,DP PLOWED LG CL
83	5.7	17.4	306	283	312	301	BARE,DP PLOWED
89B	6.8	16.8	299	264	304	278	OLD CABBAGE + WEEDS
89D	6.8	16.8	301	276	310	287	OLD CABBAGE + WEEDS
91	27.8	32.4	300	272	306	235	SPINACH
94	****	****	299	264	306	277	BARE
96W	6.4	14.4	305	280	316	278	BARE,FURROWED LG CLD
96E	****	****	298	239	301	248	BARE,FURROWED LG CLD
97	****	****	298	250	301	263	BARE,FURROWS IRR-3/1
99A	****	****	303	281	***	255	BARE,FURROWS IRR-3/2
99C	7.8	19.4	304	281	316	299	BARE,FURROWED SM CLD
104	6.7	17.3	306	287	311	299	BARE FURROWED SM CLD
105	22.3	22.3	302	277	311	291	BARE FURROWED SM CLD
107	14.2	22.2	305	286	317	299	BARE FURROWED SM CLD
109	****	****	298	246	301	261	BARE,IRR-3/1
111	8.4	22.8	307	286	315	299	BARE,FLAT CRUSTED SF
113	10.1	22.6	306	288	314	301	BARE,FURROWED LG CLD
116	16.0	21.0	305	286	314	299	BARE,FURROWED SM CLD
117	****	****	301	276	307	293	PASTURE
120A	35.0	****	299	256	301	267	YOUNG CORN PLANTS
120B	35.0	****	298	247	301	257	BARE,FURROWED SM CLD
122	13.5	21.1	305	283	313	300	BARE,FURROWED SM CLD
124	16.0	27.4	307	285	313	295	BARE,FURROWED SM CLD
127	13.3	28.8	308	289	313	301	BARE,FURROWED SM CLD
129	14.1	28.5	308	281	313	301	BARE,FURROWED SM CLD
129A	49.0	50.3	299	256	299	243	BARE,FURROWED SM CLD
131A	****	****	303	282	***	291	BERMUDA GRASS
131B	****	****	306	286	311	297	STUBBLE
132	8.2	17.2	307	285	310	300	BARE,DP PLOWED LG CL
134	9.1	20.8	306	284	314	301	BARE,FURROWED SM CLD
136	23.8	25.7	306	285	314	299	BARE,FURROWED SM CLD
139	25.2	25.3	306	285	315	297	BARE,FURROWED SM CLD
140	30.8	30.8	302	276	307	289	SM SORGHUM PLANTS
143A	9.8	20.0	308	282	***	303	BARE,DP PLOWED LG CL
143B	13.0	19.2	308	287	***	300	BARE,FLAT SMALL CLOD
143C	15.0	16.8	308	283	***	294	BARE,FURROWED SM CLD
144	15.0	25.5	305	283	***	299	BARE,FURROWED SM CLD

BT - MICROWAVE BRIGHTNESS TEMPERATURES FOR LOW ALTITUDE (0.9 KM) PASSES
IR - GROUND BASED IR TEMPERATURES

NUMBER OF OBSERVATIONS 42

To illustrate result 1), when the linear correlation coefficients for the 1.55 cm data were calculated, the results were poor ($\simeq 0.6-0.7$); only for the February 25 flight over Phoenix was the correlation between the microwave brightness temperatures and soil moistures good ($\simeq 0.9$). However, the correlations between the brightness temperatures measured at different times for a given field were good at all 3 sites ($\simeq 0.9$), indicating reproducibility of the data. The reason for the poor correlation results can be seen in Figure 6, which is a plot of the 1.55 cm brightness temperatures from the flights on March 1 and 2 over the Weslaco test site. We see that there is little or no change in the brightness temperature for soil moisture up to about 22%, which is the wilting point for the Harlingen clay. Above this value, the brightness temperature decrease at the rate of 1.8°K/% soil moisture. The 10-15°K difference between the flights observed for the drier fields is primarily due to a corresponding difference in surface temperature. This non-linear result was also observed for a group of fields having a clay loam soil from the Phoenix area, as shown in Figure 7. Here again there is essentially no change in brightness temperatures for soil moistures less than 10 or 15%, which is approximately the wilting point for this soil type. Above 15%, the slope is 3°K/% soil moisture. This effect was also observed in the Imperial Valley data, as shown in Figure 3 at 21 cm and in Figure 8 at 1.55 cm.

Similar results were calculated for the emissivity as a function of soil moisture using the Fresnel relations for a uniform soil model, as shown in Figure 9. The complex dielectric constants used in this model were obtained from laboratory measurements at a wavelength of 0.8 cm on the soil samples listed in Table 3 (Geiger, 1972). Qualitatively, the agreement with the aircraft observations, as shown in Figure 7, is quite good. The quantitative differences can be accounted for by the rough surfaces and non-uniform moisture distribution of the observed fields.

At low values of the soil moisture, the water is tightly bound to the soil particle and thus does not significantly change the dielectric properties of the soil. For higher values of soil moisture, the water fills the pore space between particles and would behave as free water, greatly effecting the dielectric properties of the soil. This is the water that can move under capillary and gravitational forces and thus is available for evapotranspiration. Since it is this water that affects the microwave emission from the soil, this emission will indicate the water available for evapotranspiration independent of soil type.

The study of the effects of surface condition and look angle on the emission from soils was performed using the linear regression analysis of brightness temperature vs. soil moisture. This analysis was applied only to the data from the February 25 flight over Phoenix because these data are described reasonably

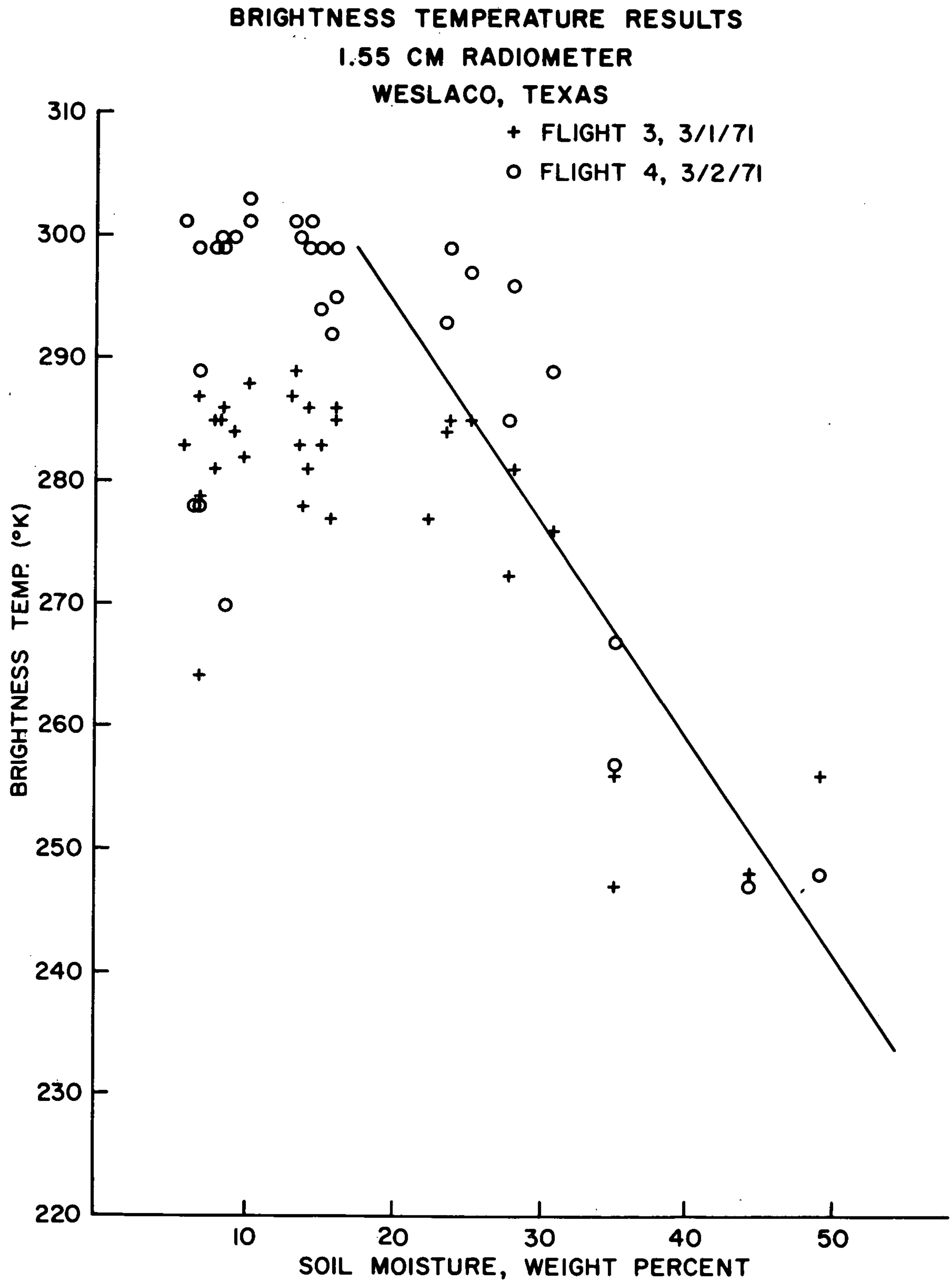

Figure 6. Plot of 1.55 cm Brightness Temperatures vs Soil Moisture from Weslaco, Texas. This data is for a heavy clay soil.

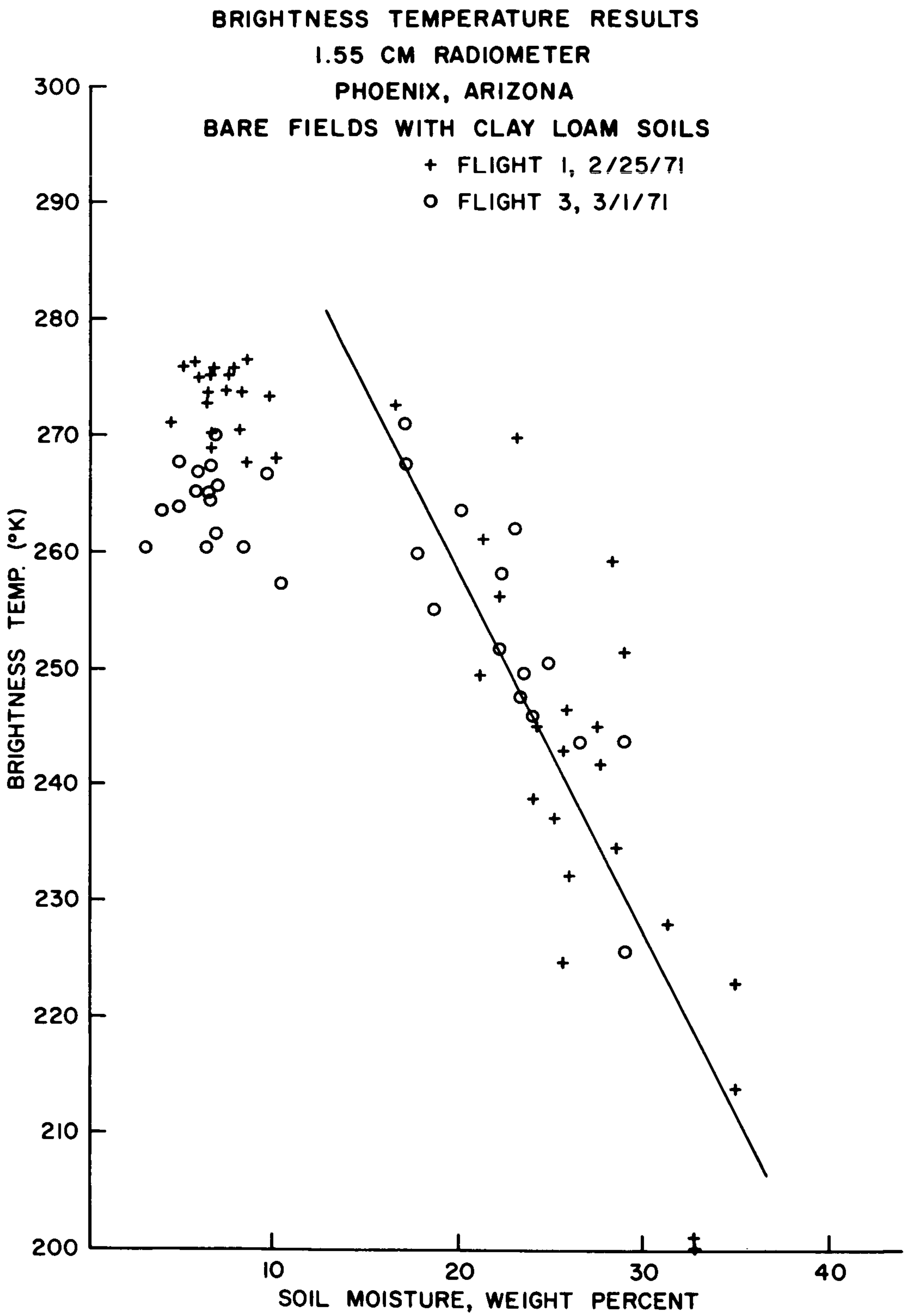

Figure 7. Plot of 1.55 cm Brightness Temperatures vs Soil Moisture from Phoenix, Arizona. This data is for a clay loam soil.

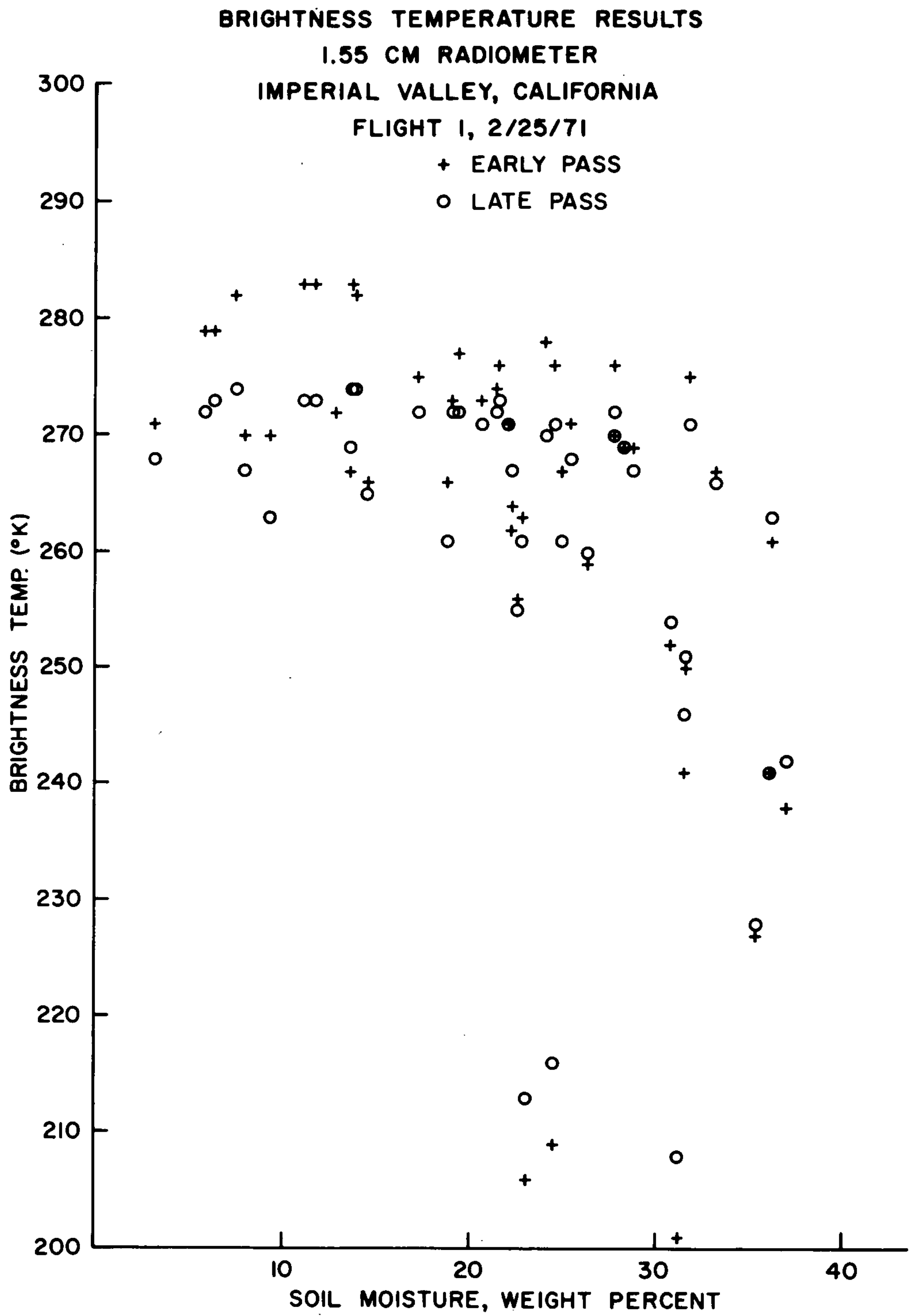

Figure 8. Plot of 1.55 cm Brightness Temperatures vs Soil Moisture from the Imperial Valley. The 3 fields with brightness temperatures below 220°K have sandy loam soils, the other wet fields are clay loam.

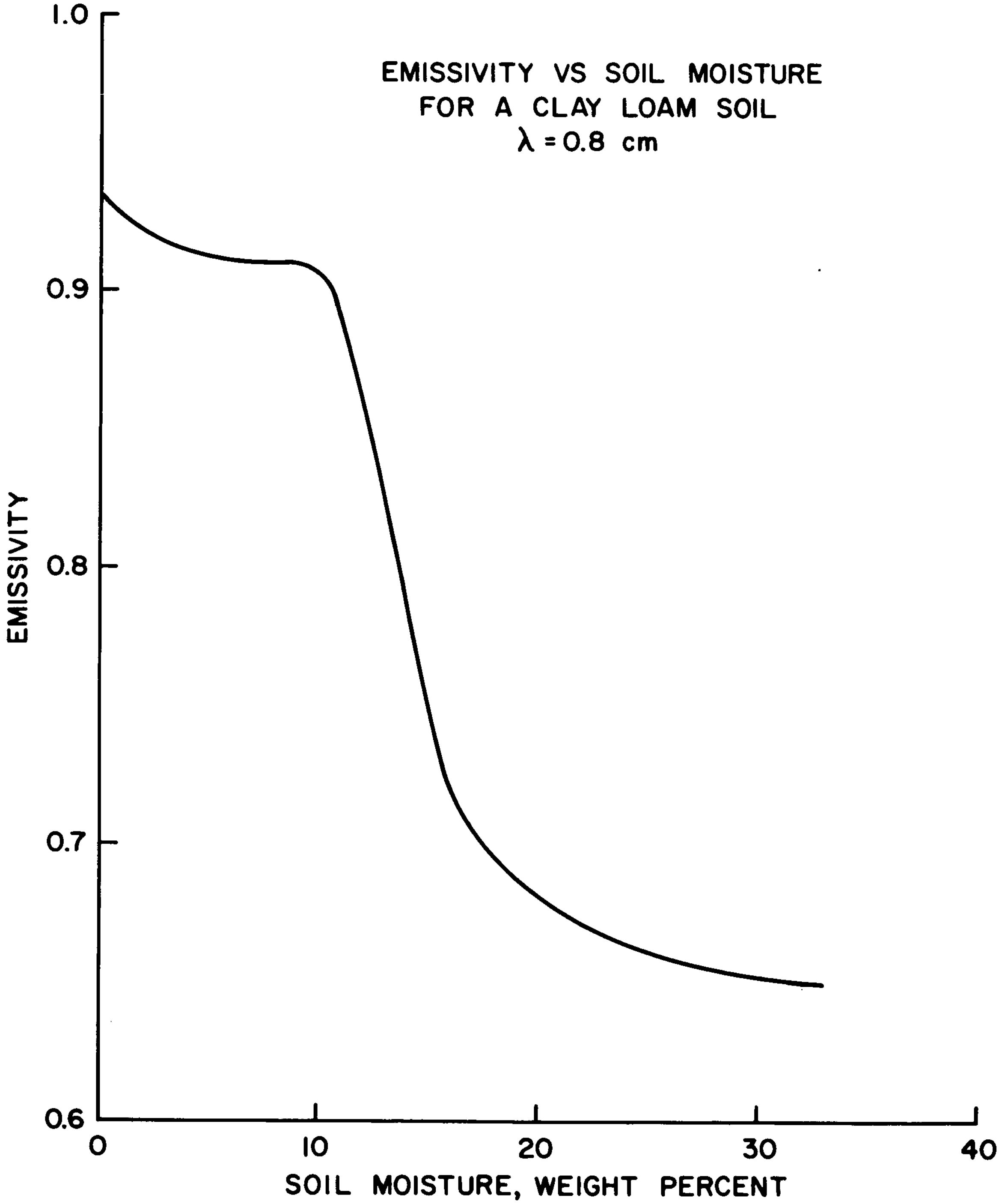

Figure 9. Plot of Calculated Emisivity vs Soil Moisture for a Uniform Soil Model

well by a linear curve. In this analysis, the slope of the line was used as a measure of the sensitivity of brightness temperature to soil moisture and the standard estimate of error was used to check the validity of a linear fit. Table 12 is a presentation of regression results for 121 bare fields and 149 bare plus vegetated fields. In each case the fields were broken into 4 groups.

(a) $\theta < 22°$ with smooth surface,

(b) $\theta < 22°$ with rough surface,

(c) $\theta > 22°$ with smooth surface,

(d) $\theta > 22°$ with rough surface,

where θ is the look angle to the field center. Rough fields are those which are furrowed or have been plowed. The quality factor, QF, is the slope divided by the standard deviation of the slope. In each case the quality factor was about 8, indicating a well-defined slope. The results for bare fields show that the slopes for the rough field cases are approximately 2/3 those for the smooth fields indicating that the radiometer was less sensitive to soil moisture in rough fields. Including a small number of vegetated fields into the analysis had the effect of decreasing the slope in every case. No attempt was made to break the groups into different soil types because the number of samples in each group would have been too small for a meaningful regression. In conclusion, the presence of either vegetation or surface roughness appears to decrease the sensitivity of brightness temperatures to soil moisture.

There is also a 15-20% decrease in the sensitivity (slope) for look angles greater than 22°. This is contrary to the expected result assuming a uniform dielectric but is reasonable in the real case where there is an increase of moisture with depth and decreasing penetration with increasing view angle.

CONCLUSIONS

This experiment demonstrates that it is possible to monitor soil moisture variations with airborne microwave radiometers. The data presented here indicate that there is little change in the emission from soils with moisture contents less than 10 to 20% and above this point there appears to be a linear decrease at about 2°K/% soil moisture. The value of the knee in the curve depends on the soil type and may be related to the wilting point of the soil. This is also a feature of the uniform dielectric model in which the emissivity is calculated from laboratory measurements of the dielectric constant. It has also been shown that both surface roughness and vegetative cover decrease the ability to sense soil moisture at least at 1.55 cm.

Table 12

Linear Regression Results - Phoenix, Arizona
Flight 1 - February 25, 1971

	BARE FIELDS					
	$\theta < 22°$					
	n	Intercept	Slope	Q. F.	Std. ERR. of Estimate	Corr. Coeff.
Smooth	23	285	-1.88	8.9	9.4	0.888
Rough	30	281	-1.33	11.9	4.3	0.914
	$\theta > 22°$					
Smooth	23	280	-1.66	8.8	10.1	0.887
Rough	45	276	-1.08	7.3	8.8	0.745

	ALL FIELDS					
	$\theta < 22°$					
	n	Intercept	Slope	Q.F.	Std. ERR. of Estimate	Corr. Coeff.
Smooth	33	286	-1.69	8.4	9.7	0.832
Rough	34	280	-1.27	11.5	4.4	0.897
	$\theta > 22°$					
Smooth	31	281	-1.52	7.8	10.9	0.823
Rough	51	276	-1.07	7.8	8.3	0.745

From the multi-frequency data, we conclude that the longer wavelength radiometers (6 and 21 cm) have greater sensitivity to soil moisture. This was indicated by the larger slopes determined by regression analysis and the greater temperature differences between wet and dry fields.

As can be seen from the high scatter in the data, a considerable improvement in the quality of this data is necessary before quantitative relationships between microwave emission and soil moisture can be determined with confidence. Toward this end, more detailed field descriptions and moisture measurements have been made to support a 1972 series of flights. In addition, the flights were planned at a lower altitude, 0.6 km, to afford better resolution with the radiometers. This should enable us to learn more about the effects of the moisture profile, soil type, and surface condition on the emission from the soils.

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